Innovative Infrastructure Solutions (2023) 8:187
https://doi.org/10.1007/s41062-023-01147-0

REVIEW

The role of construction materials by accelerated carbonation in mitigation of CO_2 considering the current climate status: a proposal for a new cement production model

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Received: 12 December 2022 / Accepted: 11 May 2023 / Published online: 1 June 2023

Abstract

This work presents the evolution of carbon dioxide (CO_2) emissions to the atmosphere with data from 2009 to 2019, considering three sources and respective emission sectors. In the first section, a reflection on CO_2 emissions today is developed to compare the amount that has been removed from the atmosphere with present technologies and systems. Secondly, the current study consists, in part, of a scrutiny of the areas and subareas of capture, utilisation and storage of CO_2 that are considered nowadays. A revision on the current development of a direct air capture technology regarding commercial implementation, economic viability, and importance in mitigating global warming is also presented here. The importance of the construction sector (building and infrastructure) as a path to achieve climate neutrality, considering the new materials based on accelerated carbonation, is highlighted. Construction materials based on accelerated carbonation have the potential to use and store several quantities of CO_2. This work brings forward a new model of construction material production based on innovative technologies developed to reduce the concentration of CO_2 in the atmosphere, also considering its economic viability. In general, it is presented the latest research developments in building material area that allow mitigating global warming. The form of reflection concluded on the current technological development in this area and the major future challenges that still need to be achieved.

Keywords Greenhouse gas · CO_2 · Direct air capture · Accelerated carbonation · Construction material

Introduction

Reducing greenhouse gas (GHG) emissions is one of humanity's most significant challenges today. The development of civilisation over the centuries at the technological level has led to a huge demand for the exploitation of fossil resources. Energy production is done due to fossil resources (majority), and in recent decades have significantly increased CO_2 emissions into the atmosphere [1].

The increase in average temperatures on the planet is a phenomenon that occurs due to the significant emission of GHGs. Global warming concerns non-governmental organisations that monitor and study global climate change, such as the United Nations Intergovernmental Panel on Climate Change (IPCC) [2]. Climate neutrality has been set to be achieved by 2050, and it is essential not only to reduce the use of fossil fuels but also to capture CO_2 from the atmosphere [1, 3]. Of all the GHG, CO_2 and methane (CH_4) are the primary ones responsible for global warming, both of which are part of nature, and their cycle on the planet is critical to life. But the emission of these gases increases yearly, affecting the planet's climate and ecosystem [4]. The data published by the European Parliament in 2019, considering all countries of the European Union (EU), indicate that around 80% of GHGs emissions are due to CO_2 emissions and about 11% to methane emissions. However, the latter has greater effectiveness in effect [4].

Energy production is the activity that produces the most GHGs, about 70%, followed by agriculture with 10.55%,

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and at the same level, industrial processes with 9.10% and finally the recycling and reuse industry with a value lower than 3.32% [4]. The identification of GHGs emission processes is essential to reduce or reverse global warming by replacing polluting processes with more environmentally friendly ones. New production technologies not dependent on fossil fuels have been developed in energy production, but as already mentioned, this sector still represents the largest share of GHG emissions.

Once the problem is identified, it is necessary to develop new ways of reversing or stabilising the situation. Over the past few decades, various paths of energy production based on renewable sources, such as wind turbines, have been developed and installed worldwide. Energy production through wind turbine parks has grown significantly in recent years. Despite the high economic cost of the installation as well as its maintenance, however, it is a sustainable way of producing energy by avoiding fossil resources [5]. The world's annual wind power production capacity has been reported at a total of 837 GW, which given the non-use of fossil fuels, means that around 1.2 billion tonnes of CO_2 are not emitted into the atmosphere [6]. But as has already been mentioned, despite the efforts of recent decades, it is still impossible to reduce fossil fuel consumption to the desired and necessary level.

Direct air capture (DAC) is a technology that has been in place for five or six decades and has existed since the 1970s in the oil industry. The captured CO_2 is injected into depleted deposits to liquefy them, enhancing them, and thus allowing more oil extraction (enhanced oil recovery—EOR). From an economic point of view, it will enable the extraction of more than 25% of oil, but it turns out to be harmful to the climate: burning EOR products emits about 1.5 to 2 times the amount of CO_2 injected [7].

Recently, this type of technology has had significant development. Still, for a more environmentally friendly purpose, the goal is to capture the CO_2 from the atmosphere and store it in the soil. Swiss start-up *ClimeWorks* [8] presented its DAC model in 2017, which consists of directly capturing CO_2 from the atmosphere through a chemical filtration process. Nowadays, more companies are developing this type of technology, when used in filter modules, allows capturing of thousands of tonnes per day, despite that it requires a considerable energy cost. Canadian start-up *Carbon Engineering* [9], after *ClimeWorks, presented* a similar DAC model but was more economically viable.

A new DAC system has recently been introduced based on "liquid–solid phase separation", capable of removing CO_2 at low atmospheric concentrations and with 99% efficiency. This new system's rate at which CO_2 can be extracted is at least twice as fast as that of existing major DAC systems. In addition to the reaction speed and efficiency of this DAC system, it allows the removal of CO_2 in a wide range of concentrations of CO_2 in the air, from about 400 ppm up to 30% [10]. According to the study by *Fasihi* et al. [11], DAC systems are already being implemented massively, and they are divided into two categories: LT DAC (low temperature) and HT DAC (high temperature). The LT DAC requires less operating energy, but the economic cost per amount of CO_2 captured is still high, as will be mentioned in a study later.

Published data from the non-governmental institute *Global Project Carbon* [12] in 2019 indicate that about 1608 Mt of CO_2 were emitted into the atmosphere this year, only from cement production. According to Global Project Carbon, Portland cement production accounted for about 4.42% of total CO_2 emissions in 2019. However, the construction area has been involved in the issue of GHGs mitigation, and despite the values mentioned above, it is an area where new developments must be achieved in the implementation of new construction forms for CO_2 absorption and storage.

In the context of CO_2 utilisation, accelerated carbonation technology has been developed in recent decades; it can be briefly stated that it consists of a process in which, at a controlled pressure, a high amount of CO_2 is introduced into a construction material (both mortar and concrete) in its production phase. This allows not only storing CO_2 but also changes the mechanical properties of the construction material; it becomes more hardened [13–15].

In a separate way from the above, the geological cycle of CO_2 is also linked to the formation of rocks. In the planet's natural cycle, CO_2 is exchanged between the atmosphere and the hydrosphere until a balance of quantities is established; it is a natural process of CO_2 diffusion in the atmosphere, in the aquatic environment, and in above the waterline. Subsequently, CO_2 can be dissolved in rainwater producing a solution of carbonic acid (H_2CO_3) that allows causing erosion of rocks releasing calcium ions (Ca^{2+}) and bicarbonate (HCO^{3-}). In the aquatic environment, some organisms absorb these ions that are useful for the formation of their carbonated shells. After the end of the life of these organisms, these shells rich in carbonated sediments can migrate to underwater areas of high pressure and temperature that partially fuse carbonates [16]. In the aquatic environment, the presence of Ca^{2+} and CO_2 allows the formation of calcium carbonate ($CaCO_3$). This described form of mineralisation corresponds to a natural and slow process [17], on the other hand, accelerated carbonation used in the production of new construction materials is based on the same principle of reaction of Ca with CO_2, but on a process that allows the use of significantly more CO_2 and faster.

The development of innovative technologies to replace *Portland* cement is an added value in mitigating CO_2 in the atmosphere: accelerated carbonation allows the utilisation and storage of CO_2 in an analogous way to its natural geological process but in a significantly more considerable and faster amount. Construction materials based on this process also have the advantage of using industrial waste and residual streams, such as slag from steel processes [18, 19].

One of today's significant technological challenges is reducing CO_2 emissions to the atmosphere and capturing and storing it. To achieve climate neutrality in 2050, it is essential to develop and apply innovative technologies that allow capturing CO_2 from the atmosphere but also use it and store it so that it does not return to the atmosphere.

Construction materials in mitigation of CO_2

At present, several lines of scientific research related to civil engineering have focussed on the study and development of new materials and forms of construction that allow the use and storage of CO_2. The authors Li et al. [20] published a study in which they survey the new emerging technologies, related to the construction area, that allow the use of CO_2. As will be discussed later, the construction area has enormous potential as an isolated area for carbon capture and storage.

Construction materials based on recyclable raw materials, such as steel slag and mine waste, where a production process based on accelerated carbonation allows them to be alternatives to *Portland* cement, are also useful for storing CO_2 on a large scale and in a sustainable way [15]. A recently published review by Kazemian & Shafei [21] presents a synthesis of recent scientific developments in innovative materials with a focus on the use of CO_2. The construction area has had a line of evolution in which there is clearly a concern about the use of materials that make it possible to use and store CO_2. At present, there are already technological solutions for this material that are commercialised in a sustainable way [22, 23].

The present work has as its initial objective study of the evolution of CO_2 emissions by area of activity. It is essential to be known how the area of cement production has evolved in terms of environmental impact. Despite current scientific and technological developments, *Portland* cement, which is responsible for a portion of CO_2 emissions, continues to be produced and used on a large scale. A new approach is presented on the role that in future the area of construction should have in the mitigation of global warming. The new materials based on accelerated carbonation, as an alternative to *Portland* cement, have been studied and developed to be implemented commercially, at present, there are already some sustainable solutions.

The main objective of this research is to present an "ideal" model of the production, of construction materials, where the full potential of this area for the use and storage of CO_2 can be exploited. To this end, it is necessary to investigate not only the new technologies and methods already mentioned above but also the new methods of CO_2 capture as well as how they can be combined with the construction area.

Methodology

The research was carried out in a selective and specific path, on the present subject, in several scientific and non-scientific databases resulting in a bibliographic portfolio that covers the latest developments on CO_2 mitigation through the construction area. The main steps were as follows:

- It was first researched by the latest reports from non-governmental organisations on the current climate state. Has been given priority to world-renowned institutions with extensive work in this area [2].
- Following the work mentioned above, three sources were selected that allowed reliable consultation of CO_2 emissions data in the period from 2009 to 2019. This consultation was carried out between May and June 2022, and the main purpose was to consult CO_2 emissions data from the last decade, but for all three considered sources [12, 21, 22], the published data ended in 2019.
- On the *ScienceDirect* research platform, research was carried out with the following groups of words: "greenhouse gas mitigation", "carbon capture", "carbon storage and utilisation", "construction material carbon utilisation", "accelerated carbonation" and finally "direct air capture". The period defined for the research was from 2016 to 2023. After a thorough consultation of the research results and posterior work revision, a total of thirty-two scientific articles of relevant importance, for the subject, were selected. A summary is indicated in Fig. 1.

- The selected articles of the research were thoroughly studied and led to the consultation of others who are also referenced, some with an older publication date. A total of fifty-five citations are present.

Subsequently, the documents were duly analysed by the authors considering the mitigation of CO_2 using new construction materials. Each article was studied individually and from there, the authors developed all the present work based on the following topics: the current climatic status, the level of CO_2 emissions in recent years, the current capacities to mitigate this effect and finally study the role of new construction materials for a future where climate neutrality will be achieved.

Evolution of CO_2 emissions

At present, it is possible to consult the publications of non-governmental organisations with data of CO_2 emissions into the atmosphere. This data can help in the strategy of implementing new paths and ways to mitigate the effect of global warming.

Climate neutrality, which is a target to be achieved by 2050, as mentioned in the 2022 IPCC report [1], provides two fundamental strategies: one that corresponds to the reduction in the use of fossil fuels, as already mentioned, other corresponds to the capture of CO_2 from the atmosphere to significantly reduce the amount that has been accumulated over the years.

Table 1 shows the annual CO_2 emissions from 2009 to 2019, estimated by global project carbon (GCP) [12]. From the available data, the objective is to visualise the variation in CO_2 emissions by sector. As can be seen, the emission values have increased in all industries from 2009 to 2019; there is a significant difference in values by sector. Despite minor fluctuations in an intermediate period, the gradual increase is common to all. The graph of Fig. 2 shows the increase in emissions per sector.

In this work, three sources of CO_2 emissions were consulted in the period previously mentioned, as indicated in Table 2. Not all sources show their accounting of emissions by the same sectors, and even when they do, there are minor discrepancies. Figure 3 also indicates the total annual CO_2 emissions published by the Potsdam Institute for Climate Impact Research (PIK) [24] and the World Research Institute (WRI—CAIT) [25]. In the three sources compared, there was an apparent increase in total CO_2 emissions; the trend is similar despite the slight discrepancy in values.

In general, it can be said that CO_2 emissions into the atmosphere have increased between 2009 and 2019, despite intermediate fluctuations by sector; it is not only confirmed by the values consulted from the three sources considered but with a similar trend of increased emissions sum values. Concern about CO_2 emissions by governmental and non-governmental organisations has existed in recent years, but as seen in Fig. 3, the emissions have increased significantly between 2009 and 2019. The values corresponding to these years are indicated in Table 2. In 2009, emissions were below 32,000 $MtCO_2e$, and in 2019, they are already close to 37,000 $MtCO_2e$; of the three sources consulted, the values do not differ much from each other and indicate a growth of about 5000 $MtCO_2e$ in the emission rate from 2009 to 2019.

Table 1 CO_2 emissions estimated in 2009–2019 [12]

Emissions $MtCO_2e$ ×10^3					
Year	Cement	Coal	Gas	Gas flaring	Oil
2009	1170	13,067	5761	0.367	10,996
2010	1248	13,970	6207	0.366	11,304
2011	1343	14,781	6379	0.353	11,334
2012	1378	14,949	6509	0.363	11,496
2013	1439	15,042	6554	0.369	11,583
2014	1494	15,062	6661	0.381	11,629
2015	1437	14,718	6787	0.371	11,878
2016	1479	14,360	6969	0.387	11,957
2017	1500	14,453	7118	0.422	12,128
2018	1566	14,718	7459	0.411	12,187
2019	1608	14,573	7555	0.434	12,227

Table 2 Total CO_2 emissions 2009-2019

Emissions $MtCO_2e$ × 10^3			
Year	Total (fossil and cement) GCP [12]	Total WRI CAIT [25]	Total PIK [24]
2009	31,603	31,801	31,100
2010	33,340	33,360	32,700
2011	34,465	33,264	33,800
2012	34,971	33,657	34,400
2013	35,280	34,302	34,700
2014	35,532	34,689	35,200
2015	35,494	34,560	35,100
2016	35,450	35,224	35,000
2017	35,923	35,736	35,400
2018	36,643	36,669	36,100
2019	36,699	36,874	36,200

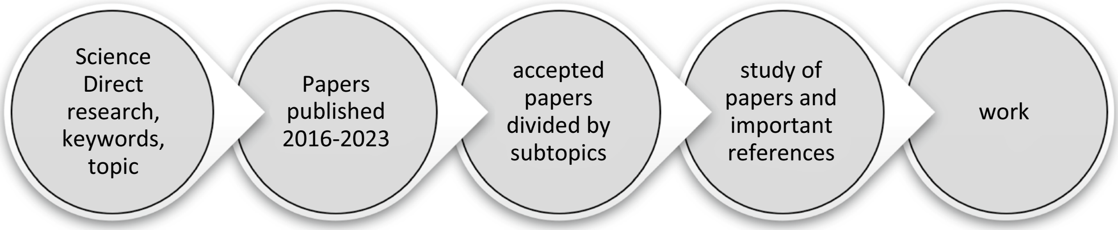

Fig. 1 How papers were screened and selected for this work

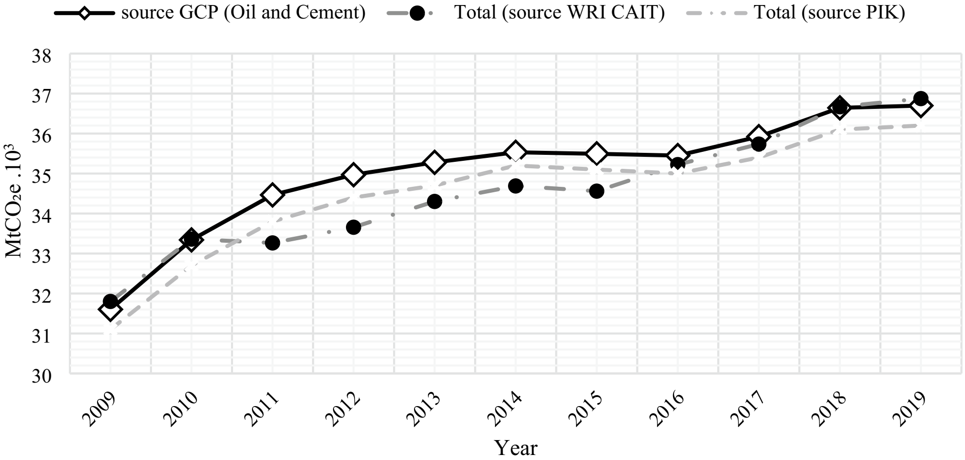

Fig. 2 Evolution of CO_2 emissions 2009–2019 [12]

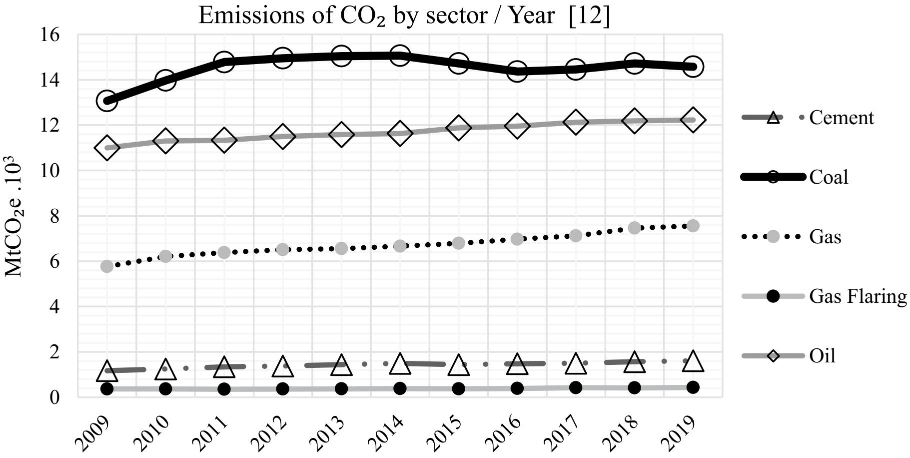

Fig. 3 Total annual CO_2 emissions by source, 2009–2019

With the consulted emissions data, it is possible to conclude that the emission rate from 2009 to 2019 increased significantly in the order of 5000 $MtCO_2e$. In this period, more than thirty thousand $MtCO_2e$ were issued yearly and increased from year to year. Table 2 shows only slight fluctuations in intermediate years, as already mentioned.

The only way to mitigate global warming caused by the CO_2 GHG effect is to reduce its concentration in the atmosphere significantly. This need involves reducing emissions to counter the trend of increasing the annual emission rate, evidenced in the graph of Fig. 3, and capturing and storing the CO_2 that has accumulated in the atmosphere yearly.

Sectors for CO_2 capture and storage

The capture and storage of CO_2 (CCS—carbon capture and storage) is an area of activity that encompasses subareas were using innovative technologies and the exploration of natural processes; it is possible to remove CO_2 from the atmosphere and then store it, has been widely explored by a substantial number of countries [26]. As already mentioned, to combat global warming, it is necessary to reduce GHGs emissions drastically and capture what has been accumulated in the atmosphere during the last decades.

The authors Hepburn et al. [27] published in 2019 a paper dividing CCS into ten subareas, or paths, where CO_2 is captured as indicated in Table 3.

Of these ten subareas mentioned above, not all complete the overall cycle of CO_2 capture and storage. The objective of mitigating GHGs implies drastically reducing their concentration in the atmosphere, so it is necessary to consider,

Table 3 Carbon capture and storage subareas [27]

1. Industry	6. Bioenergy
2. Fuels from CO_2	7. Enhanced weathering
3. Microalgae products	8. Forestry techniques
4. Cement construction	9. Soil techniques of sequestering CO_2
5.Enhanced oil recovery (EOR)	10. Biochar

as applicable for this purpose, the areas that effectively comply with the overall cycle of CCS. The division of the ten subareas is based on the following considerations by region [27]:

- In industry, due to its processes, the CO_2 is released in the chimneys, which a filtering process, such as the DAC process, can capture. From there, CO_2 is again reused for the same processes or others similar, and a residual part is continuously emitted into the atmosphere; this process is indicated as subarea one.
- Subarea two consists of the reuse of CO_2 through its capture from the use of fossil fuels later and in a chemical process; this CO_2 is used in producing other fuels, such as methanol or methane. After burning the formed fuels, CO_2 is emitted back into the atmosphere.
- In the case of microalgae (subarea 3), as the name implies, it consists of using microalgae to capture CO_2 from the atmosphere and form bioproducts such as biomass and biofuels, once again considering the overall cycle.
- The construction using *Portland* cement is a subarea specialising in developing CCS, subarea four. In recent years, the scientific community has developed technologies representing new forms of presentation of alternative materials to *Portland* cement. These are materials based on accelerated carbonation technology; from an engineering point of view, it is a process that allows increasing the material's stiffness [28], but in this case, it is an added value for using CO_2. Recently published works showed the technical and economic viability of accelerated carbonated materials to suppress *Portland* cement-based materials [22, 23]. The construction area, in this sense, represents the complete cycle of capture and storage of CO_2: it can be used in the design of new materials that form a matrix with calcium or magnesium, which captures CO_2 over the years in a mineralisation process [31].
- As already mentioned in the introduction, the extraction of enhanced oil (subarea five) allows the use of CO_2. Still, the combustion of this enhanced oil product will enable it to be emitted back into the atmosphere in a ratio of 1.5 to 2 times more, so it is an area that does not reduce the concentration of CO_2 in the atmosphere in the medium and long term.
- The concept of bioenergy in subarea six refers to the formation and growth of forest biomass as a CCS technique, undoubtedly corresponding to a complete cycle, but of millenary level in process duration. Based on this effect, subarea nine also corresponds to a similar process of increasing the natural capacity to store CO_2 contained in organic mass through soil exploration techniques, such as agriculture.
- The other subareas, no less critical, consist of exploring and maximising the geo-biochemical cycles of CO_2 already in nature. They have high limitations, such as forestry techniques (subarea eight); in urban centres, it is very limited, but in general, it is limited to the space available and what can be exploited from it. Subarea seven can be succinctly defined by techniques of spreading crushed rocks underground, like subarea ten, but here it uses charcoal to store CO_2.

CCS plays an important role in reducing GHGs, all subareas have a relevant role. Author Shu et al. [32] present a study in which they refer to the relevant role of the cement area, as well as the DAC systems that can be properly associated. In this regard, the reduction of the concentration of CO_2 in the atmosphere will be significant from 2045 onwards. In the recent study by McLaughlin et al. [33], it is evidenced the future work of global implementation that needs to be done as well as the association of areas and the interdiscipline of technologies, with the area of cement production being one of the targets.

The current state of CCS

The *global CCS Institute* recently published a report where it is possible to consult values regarding CCS for certain areas [34]. From the point of view of the emissions data, it is possible to compare with the CCS values to balance the current situation. The data presented here relate to 121 countries that are part of the *Climate Ambition Alliance: Net Zero 2050* [35].

Table 4 shows the annual CCS values that include industrial production, enhanced oil extraction, ethanol production,

Table 4 CCS installations in September 2021 and their capacity [25]

	Operational	Under construction	In advanced development	In project phase	Operation suspended	Total
No	27	4	58	44	2	135
Capture Capability [Mtpa]	36.6	3.1	46.7	60.9	2.1	149.3

Mtpa – million tonnes per year

natural gas processing and petroleum refinement, fertiliser production, energy production, hydrogen production, cement production, waste treatment, and DAC facilities.

About the data indicated in Table 4, it is verified that in 2021 there were twenty-seven installations with a capture capacity of 36.6 Mtpa; this means that in one year, there is the capacity to capture 36.6 $MtCO_2e$, mention that in 2019 a total of 36,699 thousand $MtCO_2e$ was emitted into the atmosphere [12]. Considering the facilities under construction, development and design, the total capacity could reach 147.1 Mtpa (excluding suspended operations). Considering these recent data [25], it is reasonable to state that the full CO_2 capture capacity falls short of the total emissions value. It should also be noted that the capture values referred to in Table 4 are not all geologically stored in the soil; a significant part of the captured CO_2 is used to extract enhanced oil.

This data query concludes that it is still a considerable way ahead until the effect of global warming can be reversed. As indicated in the IPCC report [1], it is necessary not only to reduce CO_2 emissions due to reducing fossil fuel utilisation but also to consider capturing and storing it in a way that significantly reduces its concentration in the atmosphere. In this path, the CCS gains significant importance considering the subareas referred to above, which have done a complete cycle of capture and storage of CO_2 [27].

In the present work, despite a general study on the current state of CO_2 emissions and their policies implemented to mitigate the effect, as well as the recent advance of technologies and commercial areas implemented to capture and store CO_2; a particular focus is given to the subarea of construction (cement). All sizes and subareas should be explored and combined to combat global warming so that the sum of individual contributions is relevant to lower the emission values, already mentioned here.

The present scientific and technological challenge is high, but in recent years, necessary steps have been taken to implement innovative technologies to mitigate the long-term GHG effect [33]. The new DAC technology has made significant advances at present, has economic and implementation aspects that still need to be improved, but in the last decade has had significant developments; the author Marchese et al. [36] present research into the economic and industrial viability of co-use of DAC systems such as the *Fisher–Tropsh* process (chemical process for the production of liquid hydrocarbons) as a way of reducing fossil fuels, and another example was presented by Sing & Colosi [37] which described a DAC system that is electrically powered by excess energy from renewable sources.

The question that needs to be asked is which paths must be followed that allow not only in the short term but also in the medium and long term to mitigate the concentration of CO_2 in the atmosphere effectively. CCS should be considered a complete capture and utilisation cycle to store CO_2 and thus gradually achieve climate neutrality.

One type of CCS is represented in the conventional construction area at present days; many of the materials have calcium in their constitution, which is a long and natural geological process that captures and stores CO_2 from the atmosphere, but considering the new materials based on accelerated carbonation technology, it is possible to keep CO_2 on a large scale in material production phase [29].

Today's CO_2 capture systems

The DAC system of direct capture of CO_2 from the air is a chemical process of filtering and absorption of CO_2; it is possible to consider as an example one presented *by Fasihi* et al. [11], and this publication also illustrates the functional scheme of the generic DAC system. Figure 4 shows the three main steps of this type of air-filtering process.

In September 2021, *ClimeWorks was* installed in Iceland, today's largest DAC facility; the name is O*rca* [38], and it can capture more than 4000 t of CO_2 per year. Despite being developed and even implemented commercially, the DAC process is still the subject of research with a view to its optimisation [39]. On another path, new systems are researched to improve the capacity of the materials used in this system as absorbents [40]. The diversity of DAC systems is excellent today; considering the material used to react with CO_2, various materials and solutions have been the research subject in recent years [32, 33].

Many developed countries have implemented biofuel production systems that work with DAC systems [43]. Currently, it is widely considered of high importance, the DAC systems in the task of CO_2 reduction combined with other areas [44].

One of the significant current challenges for this type of system is economic viability; in addition to the cost of the equipment, its operation requires a high energy cost. The authors Daniel et al. [45] present the study of a DAC system in which they also consider an economic analysis where they predict a cost of $382 per tonne of CO_2 captured. On the other hand, Fasihi et al. [11] publish a more general economic study on the cost of operating DAC systems with short-term forecasts. In general, it divides the systems into two categories: those with low-temperature solid absorbents (LT DAC) and high-temperature absorbers (HT DAC). The costs estimated through a conservative economic study are shown in Table 5 [11].

Consulting Table 5, it is verified that LT DAC systems are more economical, but currently, the cost is high, about $222/t CO_2. The same study indicates a high decrease in price by 2050, reaching a value of $54/t CO_2 (DAC LT). As already mentioned, this technology is currently facing

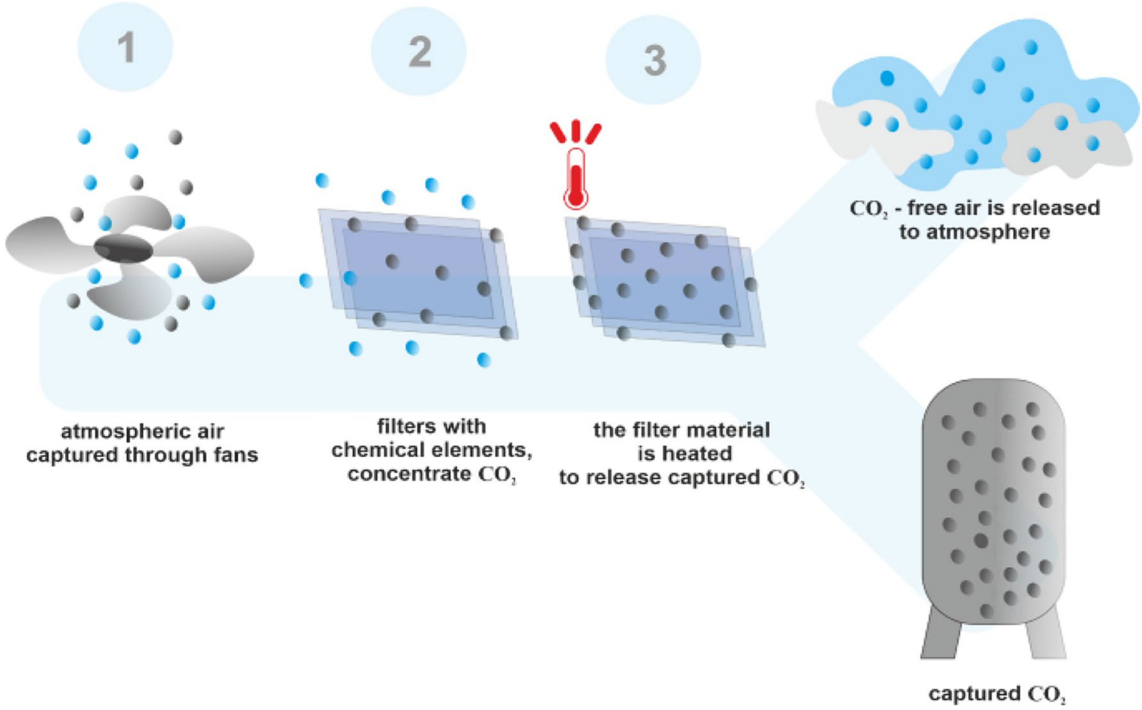

Fig. 4 Direct air capture (DAC) main steps

economic viability difficulties. However, it is predicted that this type of obstacle will be overcome.

If, on the one hand, DAC systems are used even in areas where the CO_2 concentration in the air is low, another essential system is the capture in industrial chimneys, i.e. in areas where the CO_2 concentration is high. One example is the *Cleanker* project [46], coordinated by the *Piacenza Energy and Environment Laboratory* [47] with the participation of thirteen more laboratories. This project investigates innovative technologies to capture CO_2 in industrial cement production units. Another example of the capture of CO_2 directly in the cement production industrial unit, which is already in operation, is the industrial unit called Norcem Brevik [48] of *Heidelberg Materials* [49], which is in southwestern Norway. It consists of a technologically advanced process in which CO_2 is directly captured in the chimneys of the production unit and then transported and stored securely in the soil.

Table 5 Economic study of CO_2 capture through DAC systems [11]

Year	Capture cost \$/t CO_2	
	HT DAC	LT DAC
2020	268	222
2030	133	105
2040	91	64
2050	71	54

The capture of CO_2 has evolved in recent years, both in terms of research and development as well as implementation. Still, in future, economic viability needs to be achieved so that DAC systems and the captures of CO_2 in industrial chimneys are implemented massively.

A proposed new model of cement production

Cement production is an area that in 2019 was responsible for the emission of about 1,608 $MtCO_2e$ [12], and this data is related to the *Portland* cement industry. A significant part of this type of material has calcium (Ca) in its composition, which allows, in a geological process, to capture CO_2 over centuries. In recent decades, one of the technologies that have been the target of research is accelerated carbonation [31]. This makes it possible to design new alternative materials to *Portland* cement which can drastically reduce CO_2 emissions from this industry [18].

The current challenge of achieving climate neutrality requires a scientific and technological effort to find solutions in almost scientific areas. As seen in the bibliographic research, it is concluded that there are critical areas of activity to mitigate the GHGs effect. In future, a potent combination of CCS subareas must be considered and researched, or all of them, to achieve the main objective of a neutral climate. Each subarea of CCS mentioned

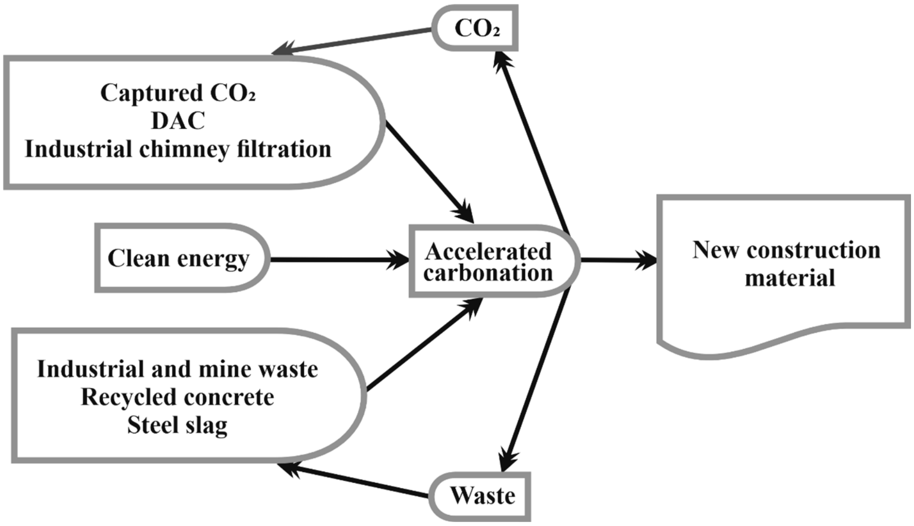

Fig. 5 The "ideal" model of construction material production based on accelerated carbonation

above may have a negligible effect on the overall goal. This is often related to the economic cost of the activity, the change in global industrial philosophy, social acceptance, and understanding. The recent study by Soares et al. [50] refers to an alternative material to *Portland* cement. In contrast, it is designed using recycled materials from industrial waste in a circular economy model.

Considering the current state of the art, *Portland* cement production should evolve into a more environmentally friendly model based on recycling valuable materials. A general circular economy model can be designed considering the various aspects of the production of construction materials using accelerated carbonation to use CO_2 captured by DAC systems, direct captures in industrial chimneys, or from other sources [13]. But also, with the consideration of reutilization, the industrial waste materials, and mining processes waste [51], or even recycled concrete [52] that in an elevated temperature production system may have better mechanical properties [53]. Waste from steel processes is also a valuable source of raw material for obtaining new construction materials based on accelerated carbonation [54]. Many of these waste materials are accumulated over decades without any type of significant and appropriate use [19].

The implementation of a model for the use of CO_2 in the *Portland* cement industry, considering its economic viability, depends on the provenance of $CO_{2,}$ as concluded by Monteiro & Roussanaly [30].

The ideal model is indicated in the diagram in Fig. 5, consisting of the production of construction materials with raw materials derived from recyclable waste that can be used, with the use of clean energy and CO_2 captured from the atmosphere through DAC systems and other fonts. All industrial production is based on accelerated carbonation technology, and the residual CO_2 and the excessive waste (produced) are reused again.

The final construction material produced in this model requires an interconnection between various sectors. Still, it allows the development of a construction area that completes an overall cycle of CCS: the captured CO_2 is stored sustainably (DAC systems). The biggest challenge of the application of the model is its implementation in an economically sustainable way in which all the areas presented in the diagram in Fig. 5 are interconnected.

The production of construction materials has a huge potential to store CO_2 [28], but this model has other advantages. In general, CCS is gradually moving to reduce its implementation costs in various areas and has been implemented successively in different industrial processes [26] and has also been the target of study-developed and sustainable logistics systems [55].

This model is presented as being " ideal" due to the absence of CO_2 emissions into the atmosphere. It consists not only of this, but it is also used and stored CO_2 in a sustainable way that is previously captured through processes such as DAC and filtration in industrial chimneys. The model consists of the interconnection of existing and implemented technologies, all together having a synergistic effect.

The use of clean energy without any CO_2 emission, such as the before-mentioned case of wind energy [6], together with the reuse of waste and the large-scale use of CO_2, allows this production process, based on accelerated carbonation, to replace *Portland* cement in a sustainable way without CO_2 emissions.

This path to be followed is daring, but it is validated by existing technologies; it only consists in the interconnection of efforts already put into practice. In fact, these materials already exist [22, 23] but their sustainability depends on the provenance of raw materials such as CO_2, their interconnection with DAC systems [45] will certainly be beneficial as well as the reuse of industrial and mining waste [54]

Final remarks and conclusions

Total CO_2 emissions to the atmosphere increased significantly between 2009–2019, as can be seen in Table 2, despite the urgency of mitigating the greenhouse gas effect. The goal of achieving climate neutrality in 2050 will hardly occur. There has been an individual effort in each specialised area to reduce CO_2 emissions, but the results of capturing CO_2 from the atmosphere (Table 4) are low considering the annual emissions value (Table 2). It concludes that it is necessary to significantly increase the volume of CO_2 captured and stored.

The DAC is a technology that has been developed and implemented over the years and recently economic study indicate that the cost of operation will drop in future (Table 5). DAC process associated with a low operating cost will make this type of activity massified because CO_2 is currently commercialised.

The construction area plays a significant role in CCS and completes an overall capture, utilisation, and storage cycle. The recent development of new construction materials based on accelerated carbonation allows CO_2 to be used and stored. This, coupled with the current development and commercial implementation of the new DAC systems, leads to the future being possible to implement a sustainable and unique model of cement production, as indicated in Fig. 5. Sustainability is based on the provenance of raw materials: CO_2 from DAC systems and industrial waste and mine that can be reused.

The reduction of the phenomenon of global warming still presents a significant challenge; despite the adverse effects already occurring on the planet, the area of construction associated with DAC and other forms of capture in a circular economy model has enormous potential that is not yet significantly being explored.

Funding Open access funding provided by FCT|FCCN (b-on). Portuguese national funds partially financed this work through FCT—Foundation for Science and Technology, IP, within the research unit C-MADE, Centre of Materials and Building Technologies (CIVE-Central Covilhã -4082), University of Beira Interior, Portugal. Financial support from the National Foreign Experts Project (G2021026031L) is also gratefully acknowledged.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical approval Not applicable.

Informed consent Not applicable.

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